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THREE-DIMENSIONAL THERMAL ANALYSIS OF A BASELINE SPENT FUEL REPOSITORY

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THREE-DIMENSIONAL THERMAL ANALYSIS OF A BASELINE SPENT FUEL REPOSITORY*

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ABSTRACT

We have performed a three-dimensional thermal analysis using finite difference techniques to determine the near-field response of a baseline spent fuel repository in a deep geologic salt medium. A baseline design incorporates previous thermal modeling experience and OWI recommendations for areal thermal loading in specifying the waste form properties, package details, and emplacement configuration. The base case in this thermal analysis considers one 10-year old PWR spent fuel assembly emplaced to yield a 36 kw/acre (8.9 w/m^2) loading. A unit cell model in an infinite array is used to simplify the problem and provide upper-bound temperatures. Boundary conditions are imposed which allow simulations to 1000 years. Variations studied include a comparison of ventilated and unventilated storage room conditions, emplacement packages with and without air gaps surrounding the canister, and room cool-down scenarios with ventilation following an unventilated state for retrieval purposes. We found that at this low power level ventilating the emplacement room has an immediate cooling influence on the canister and effectively maintains the emplacement room floor near the temperature of the ventilating air.

The annular gap separating the canister and sleeve causes the peak temperature of the canister surface to rise by 10^{o}F (5.6^{o}C) over that from a no gap case assuming perfect thermal contact. It was also shown that the time required for the emplacement room to cool down to 100^{o}F (38^{o}C) from an unventilated state ranged from 2 weeks to 6 months; when ventilation initiated after times of 5 years to 50 years, respectively. As the work was performed for the Nuclear Regulatory Commission, these results provide a significant addition to the regulatory data base for spent fuel performance in a geologic repository. Recommendations are made for future directions of thermal analysis efforts, particularly for an expansion of the unit cell concept to treat asymmetrical boundary conditions.

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INTRODUCTION

The work described in this paper was performed at the Lawrence Livermore National Laboratory under contract to the U.S. Nuclear Regulatory Commission to provide "Technical Support in the Development of Nuclear Waste Management Criteria." In the Waste Management Program, we are concerned with the performance of spent fuel emplaced in a geologic repository. An important element of spent fuel performance is the thermal behavior of the spent fuel, package, and nearby geologic medium. This paper describes the development of a three-dimensional thermal model of a spent fuel repository, and presents preliminary results from the analysis of a baseline repository in salt.

The purpose of our thermal modeling is to calculate the time-dependent near-field temperatures in the repository. The near field includes the waste form, package, immediately surrounding geologic medium, and the emplacement room. This temperature field is essential for predicting the performance of the waste form and package. This information is used directly as input to other performance models, such as structural response, brine migration, package corrosion, and waste form dissolution.

SCOPE OF WORK

The approach taken in this work was to build upon the preliminary thermal model developed during FY78. Many phases of the original model were improved, such as boundary and initial conditions, the detail of the 3-D mesh, the treatment of annular air gap and storage room heat transfer, and the expansion of graphical output capabilities. An improvement is the capability to study problems of long duration. Not only is the retrievability period of interest, but also the post-closure phase of the repository can be analyzed for times of at least 1000 years after emplacement.

A baseline salt repository for spent fuel was defined based on OWI recommendations and our own experience. The thermal model was applied to this baseline repository and temperature fields were generated for 1000-year problems, using the TRUMP (1) finite difference heat transfer code. The goal of this analysis was to demonstrate the capability of the thermal model to handle a long-term problem with a realistic package.

PRELIMINARY MODEL DESCRIPTION

The preliminary thermal model, described by Altenbach (2,3), was developed for a repository consisting of many parallel emplacement rooms, with a single row of canisters emplaced beneath the floor at regular intervals in each room. This basic approach uses a unit cell concept, which considers one canister in the infinite array and the immediately surrounding salt.

The three-dimensional (3-D) unit cell is therefore rectangular in shape, and symmetry is invoked so that only one-fourth of a canister is treated (Figure 1). Then the four vertical faces are all planes of symmetry and have adiabatic boundary conditions. The front and left faces slice through the canister centerline, the right face coincides with the pillar centerplane, and the back face coincides with the midplane between canisters along the room axis. The room floor is located at a depth of 2000 ft. (610 m) below the surface, and the cell extends a distance of 500 ft. (152 m) above and

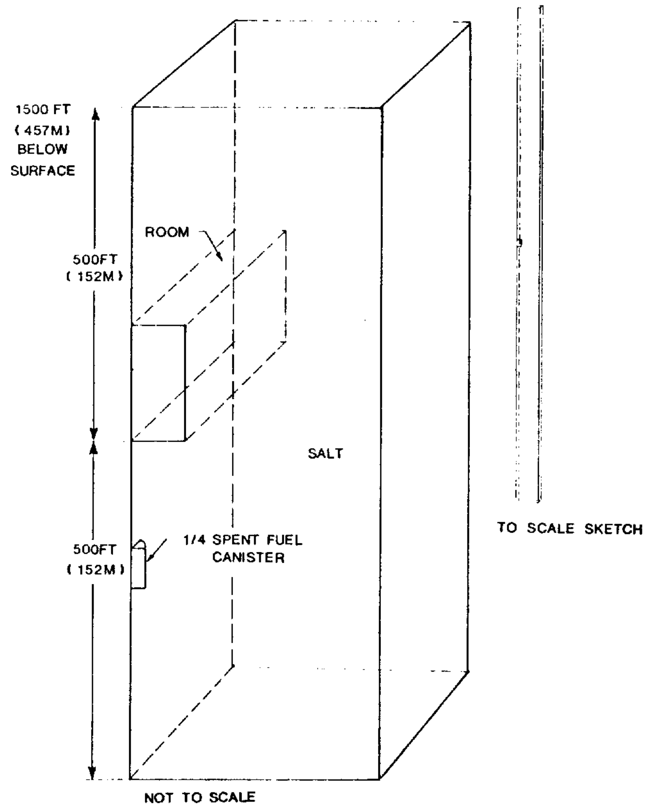

Fig. 1: Three-dimensional unit cell for preliminary TRUMP model of a geologic salt repository.

Other features of the preliminary model are summarized as follows. The heat source was modeled as a cylinder with properties of UO_2. A canister containing the spent fuel was not modeled. The waste form was assumed to be in perfect thermal contact with the surrounding salt, and heat flowed by conduction away from the source. Heat transfer modes in the room considered radiation from floor to ceiling, convection from floor to ceiling for an unventilated case, and convection from both floor and ceiling to the bulk air for a ventilated case. Heat transfer from the walls was neglected. Initial temperatures in the repository were calculated from an assumed geothermal gradient.

ADVANCED MODEL

In order to have a clearer focus for the development of the advanced thermal model, it was necessary to define a baseline design for a spent fuel package stored in a salt repository. Once developed, the model was then applied to the baseline design in a preliminary analysis. This section describes the baseline design and the rationale for selecting various parameters. The design consists of specifications for the waste form, package design, and repository design.

Baseline Design

The waste form for the baseline design consists of one PWR spent fuel assembly, which is placed in its entirety inside of a carbon steel canister. The spent fuel is emplaced in the repository 10 years after reactor shutdown, as recommended by OWI for 25-year retrievable storage of spent fuel in salt (4). The uranium content was arbitrarily set at 0.426 MTU per assembly. Calculations with the ORIGEN code set the thermal power level at the time of emplacement at 0.55 KW per canister.

In the context of a nuclear waste repository, the package is defined as everything that is placed inside of the emplacement hole. The main components of the package for a salt repository are the spent fuel assembly, canister, sleeve, and plug. The spent fuel is placed inside of the canister, which is then emplaced in a hole drilled into the floor of a mined room in the repository. The emplacement hole is lined with the carbon steel sleeve. The top is capped with a concrete plug.

The canister is designed to withstand credible handling accidents. It is 16 ft. (4.9 m) in length with a 12.75 in. (32.39 cm) outside diameter, and is constructed of Schedule 60 stainless steel. The extra space inside the canister is filled with air.

The canister is emplaced within a carbon steel sleeve of 20 in. (50.8 cm) outside diameter and 1.5 in. (3.8 cm) wall thickness (Schedule 120). The purpose of the sleeve is to isolate the canister from thermal and lithostatic stresses and to provide for easy retrievability. Between the canister and sleeve is an air gap of 2.125 in. (5.398 cm) which allows the retrieval mechanism to slide down and lift the canister from the bottom. For our purposes, the sleeve is assumed to be in intimate contact with the surrounding salt.

A concrete plug is placed on top of the canister inside of the sleeve in order to isolate the canister from the emplacement room above. The plug length is 10 ft. (3.0 m). See Figure 2.

The baseline repository consists of a series of parallel emplacement rooms, 18 ft. (5.5 m) wide and 30 ft. (9.1 m) high. The high ceiling is needed for retrieval machinery. The rooms are separated by a salt pillar of 45 ft. (13.7 m) width. The repository thermal load is set at 36 KW per acre (8.9 W/m^2) as recommended by OWI (5). This fixes the canister pitch at 10.5 ft. (3.2 m). The canisters are then emplaced in a row along the center of a room, 10 ft. (3.0 m) below the floor.

Geometric Model; Initial and Boundary Conditions

The advanced thermal model builds upon the preliminary model previously described. A unit cell with quarter symmetry is used, having adiabatic vertical boundaries. However, the top and bottom boundaries were extended and the boundary conditions modified in order to handle post-closure problems. It was found, in 50-year runs with a high-level waste source (3), that the horizontal isothermal boundaries caused a general underprediction of temperatures throughout the unit cell. This happens because the boundaries are artificially maintained at a lower temperature than they would eventually achieve from the heating of the unit cell. This effect could be significant for long-term problems.

In order to analyze a 1000-year problem, then, the top boundary of the unit cell was extended upward 1500 ft. (457 m) to the surface of the earth. Boundary conditions at the surface include (6):

- Solar heat flux of 73 Btu/ft.^{2}-hr. (230 W/m^2)
- Re-radiation to space (sky temperature of 45°F (7.2°C), earth's surface emissivity of .3).

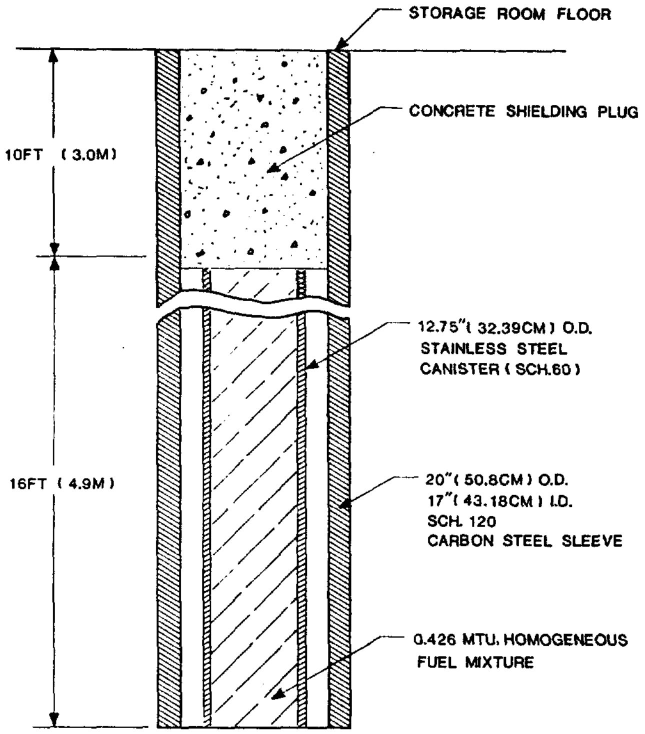

Fig. 2: Emplacement package details.

- Convection to ambient air (air temperature 66°F (19°C), convective heat transfer coefficient of 3.1 Btu/hr.ft.^{2}°F [17.6 W/m^2°C]).

Perturbations from seasonal variations in these parameters are known to disappear fifty feet from the earth's surface (6). Since our concern here is to predict temperature responses near the heat source (as opposed to the far field, i.e., earth's surface response), measured values were averaged over a one year time span to provide these numbers.

It was found, through simplified one dimensional modeling, that the medium 4500 ft. (1372 m) below the heat source would experience negligible temperature rise in 1000 years. This allowed us to place an isothermal boundary at this point which would essentially simulate a semi-infinite medium.

Initial temperatures throughout the cell were obtained by applying an appropriate geothermal flux (140 Btu/ft.^{2}-year) [1.59×10^6 J/m^2 - yr] (Ref. 7) to the bottom of the cell and allowing it to reach steady state without either the canister heat source or emplacement room ventilation. The temperature at the lower boundary is then fixed as an isothermal condition, which continues to apply the geothermal flux as long as the thermal "wave" from the heat source does not reach the boundary throughout the period of analysis. The emplacement medium directly surrounding the canister, up to 1500 ft. (457 m) above it, and down to the lower cell boundary consists of bedded salt. The remaining 500 ft. (152 m) up to the surface of the earth is arbitrarily modeled as a homogeneous material with constant thermal properties representing an approximate average of granite, shale, and basalt.

Air Gap and Emplacement Room Heat Transfer Characteristics

The baseline design includes a 2.125 in. (5.398 cm) air gap separating the spent fuel canister and the sleeve. Since the convection and radiation heat transfer across such a gap is not readily handled by TRUMP, a methodology was developed to model this phenomenon by means of an "analog conductivity" approach (8). Vertical enclosed flat plate convection correlations are coupled with gray body radiation exchange properties (emissivities and view factors) in an iterative procedure. The required heat flux is fixed, as well as one gap surface temperature. Then the radiation and convection equations are solved to yield the other gap surface temperature. Knowing the heat flux, the average gap temperature, and the annular gap dimensions, an equivalent conductivity can be determined that represents the thermal conductance of the gap at a given average gap temperature. This process yields a set of temperature/conductivity pairs that are easily used by TRUMP to simulate the convection and radiation heat transfer.

Emplacement room heat transfer is modeled as either ventilated or non-ventilated. Correlations developed by McAdams (9) and summarized by Davis (10) represent the ventilated situation with convection heat transfer coefficients as follows:

From floor: $h = .22\ (T_f - T_\infty)^{1/3}$
From ceiling: $h = .068\ (T_c - T_\infty)^{1/4}$
From walls: $h = .19\ (T_w - T_\infty)^{1/3}$

where temperatures are in °F, h is Btu/hr-ft.^{2}-°F, and T_∞ is the bulk temperature of the air flowing through the repository. In this analysis, T_∞ was set at a constant 79°F (26°C).

Convection heat transfer in the non-ventilated case is modeled with a correlation developed for enclosed spaces (10): $h_s = 0.125\ (T_f - T_c)^{1/3}$, where h_s is the coefficient for floor to ceiling convection, and T_f and T_c are those surface temperatures. For our purposes, this heat transfer was modeled as a two-step process of convection from floor to air and from air to ceiling. The convection coefficient for each step is then given by: $h = 2\ h_s$. Convection from the walls to the air is included as before.

Time-averaged temperature differences between bulk air and the surfaces are used, and the coefficients can then be considered constant throughout the period of analysis. (For our purposes the system thermal response is relatively insensitive to the magnitudes of convection coefficients). Gray body radiation is modeled in the room, with salt surface spectral emissivity of .75.

ANALYSIS AND RESULTS

The advanced model was utilized to study three areas of concern:

1) Thermal response of the canister with and without an annular air gap.
2) Comparison of ventilated vs. non-ventilated cases.
3) Room cool-down responses for retrieval operations.

The analysis focused on the thermal responses of the canister surface, emplacement package components, the near and very near field emplacement medium, and both the air and surfaces of the emplacement room. Graphical results provide time/temperature responses and temperature distributions for selected locations.

Gap/No Gap Comparison

In previous thermal analyses (2,3), it has been assumed that the canister is placed in perfect thermal contact with the geomedium. The first study made with the advanced baseline design compared results obtained from modeling the emplacement package with and without an annular gap. The perfect thermal contact case assumed the canister to be placed directly into the salt with zero clearance, while the baseline case was analyzed as described in Figure 2, with a 2.125 in. (5.398 cm) gap separating canister and sleeve.

The net effect of this particular gap configuration is to raise the canister surface peak temperature 10°F (5.6°C) over the perfect thermal contact case.

Figure 3 shows the 1000 year temperature histories for each case. The gap, however, has no influence on the surrounding medium. The emplacement room in both cases is unventilated.

Note that the temperature history for the canister surface in the perfect thermal contact case (Figure 3) is characterized by a quick rise and sharp peak at 30 years after emplacement, followed by a decline to a minimum at 520 years, then a small rise to a broad peak around 620 years and eventual decline. This unusual double-peaked response was investigated by using simple 2-D and 1-D models to explain the behavior from the standpoint of the physical heat flows occurring as well as from the theoretical standpoint of superposition. It was concluded that the double-peaked response is due to the shape of the spent fuel decay curve and the thermal properties of salt, as inputs to the calculation. Space limitations do not permit the presentation of the complete analysis in this paper.

Comparison of Ventilated and Unventilated Cases

Methods of modeling ventilated and unventilated emplacement rooms have been described earlier. The baseline design was studied for both scenarios. Temperature histories plotted in Figure 4 show responses of the canister surface and emplacement room floor in each case. The ventilation air temperature is 79°F (26°C), circulating through the room at 10,000 CFM (283 m^3/min). At such a low power level, this ventilation effectively maintains the room floor at the temperature of the air after the first hundred years. The canister surface experiences almost immediate reduction in temperature from its initial state.

Ventilation is also effective at removing a large fraction of the heat generated. After 1 year, 55% of the cumulative heat generated has been removed by ventilation. This fraction increases to 90% after 44 years. After 30 years the rate of heat removal by ventilation exceeds the rate of heat generation, causing a decline in the average temperature of the unit cell. Sensitivity studies are needed to determine the importance of ventilation for higher canister power.

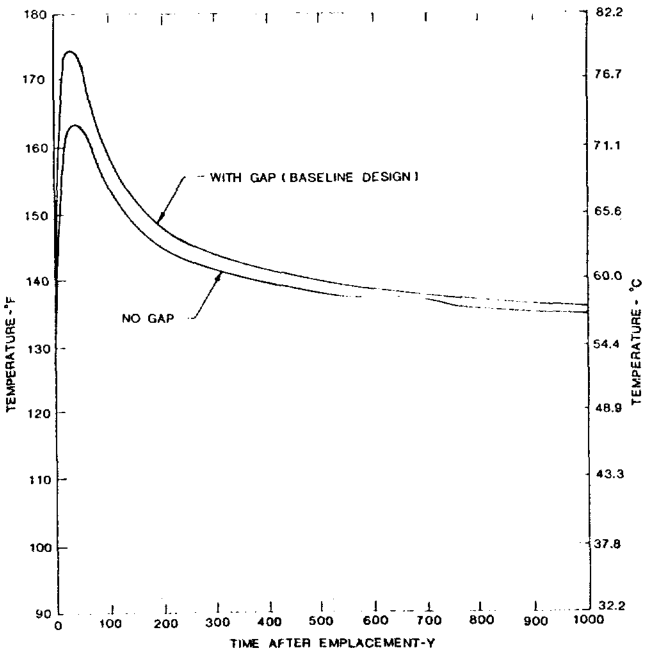

Fig. 3: 1000 year temperature histories of canister surface with and without a 2.125-inch gap separating canister and sleeve.

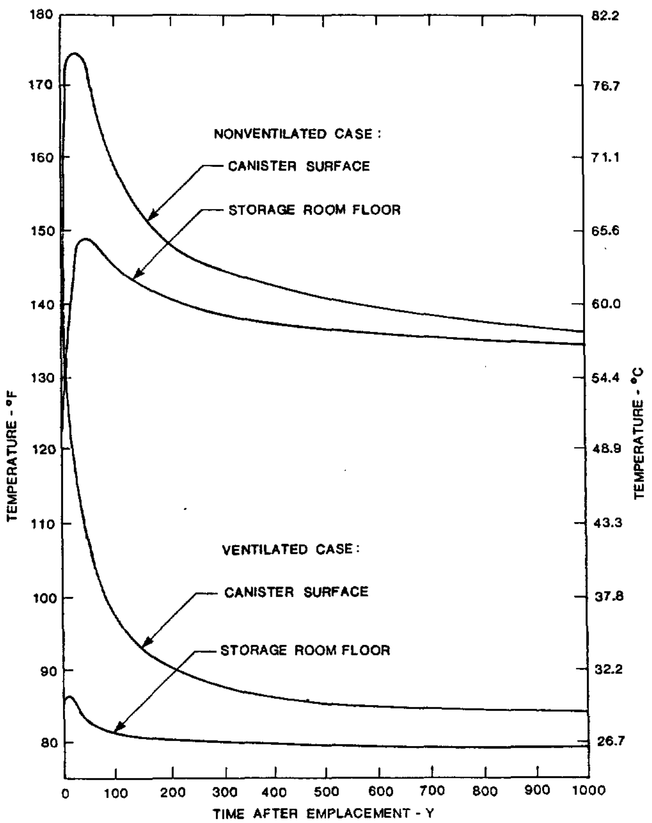

Fig. 4: Canister surface and storage room floor temperature histories for both ventilated (with 79°F air at 10,000 CFM) and unventilated cases.

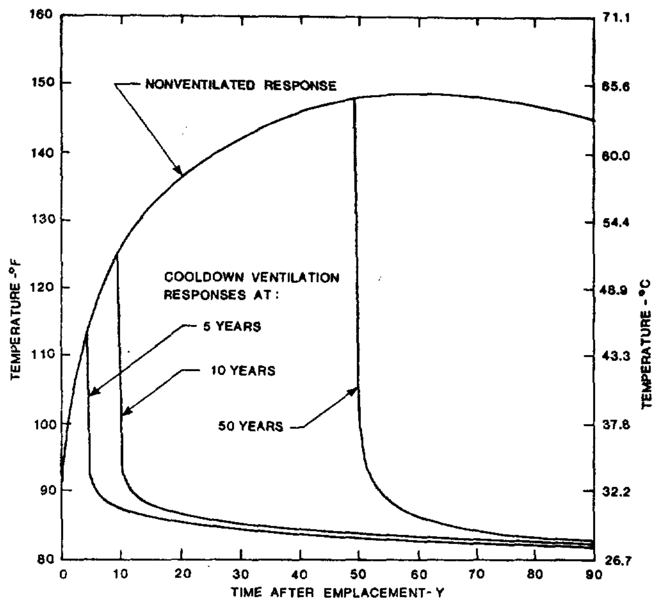

Fig. 5: Storage room floor temperature histories representing cool-down (10,000 CFM of air) from an unventilated state at 5, 10, and 50 years.

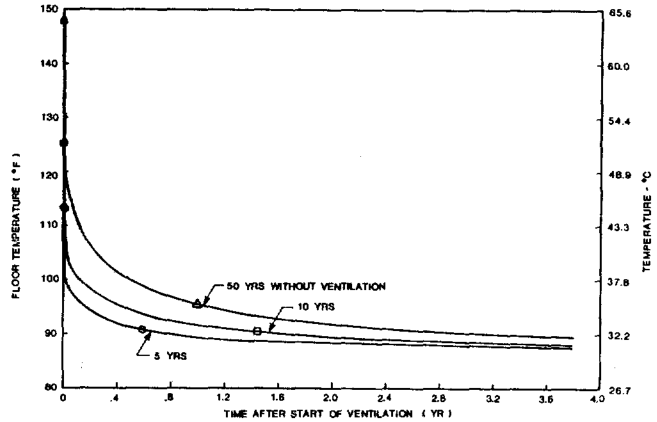

Fig. 6: Temperature response of the floor to ventilation after various periods of no ventilation.

Room Cool-Down Response

A conceivable scenario of repository operations is to close off a section of the repository (no ventilation) after it has been filled with spent fuel. At a later time, if reentry is necessary for any reason, ambient conditions in the storage room would become a critical consideration for personnel and machinery operations. Most probably a ventilation system would be activated to reduce the room temperature to an acceptable level.

TRUMP runs were executed to simulate scenarios of a non-ventilated room, with ventilation by 79°F (26°C) air initiated at 5, 10 and 50 years. Emplacement room floor temperature histories are shown in Figure 5. In 5- and 10-year scenarios the floor, which is slightly warmer than the walls or the ceiling, cools down to under 100°F (38°C) in roughly 2 weeks and 7 weeks, respectively. The 50-year case required 6 months to reach 100°F (38°C). Figure 6 shows the temperature response of the floor to ventilation for these cases on an expanded, overlayed time scale, for easy comparison of cooling times.

CONCLUSIONS AND RECOMMENDATIONS

The advanced 3-D thermal model was utilized to study a low power spent fuel emplacement. Additional detail was included to represent a more complicated emplacement package, and boundary condition refinements allowed for 1000 year simulations. An analog conductivity approach, described earlier, was used to represent the annular air gap separating the canister and sleeve.

Significant conclusions can be drawn from this analysis:

- Annular air gaps surrounding an emplaced spent fuel canister increase the canister surface temperature significantly over that expected from a perfect thermal contact case. Although the maximum temperature difference is only 10°F (5.6°C) in this low power situation, special attention should be given to gap design for higher areal power loading levels, and lower emplacement media conductivities than bedded salt.
- Ventilation at low power levels has an immediate cooling effect on the canister and effectively maintains the room surfaces at the temperature of the ventilation air.
- Emplacement room cool-down simulations showed the time required to reduce the floor temperature to 100°F (38°C) from an unventilated state to be on the order of 2 weeks to 6 months, depending on the time when ventilation is initiated. These time requirements could inhibit immediate retrieval operations.

The unit cell approach to modeling a repository is a gross simplification. For strictly thermal purposes, however, it does provide "worst case" temperature responses and can be used to bound results expected from the real problem. With these limitations in mind, the following recommendations are made for future thermal analysis work:

1) A detailed study should assess the accumulative air heating effect of many canisters emplaced below a corridor. This modeling effort used a constant ventilation air temperature, which may hold only for a particular unit cell in a corridor.
2) The unit cell method addresses one emplacement in an infinite array of canisters, all generating equal power with identical boundary conditions. Asymmetrical situations such as sequential emplacement hole loading, tunnel excavation occurring adjacent to a loaded and sealed room, and thermal effects on a canister at the edge of the array should be addressed.
3) A sensitivity analysis is needed to provide detailed information for storage room cool-down scenarios. Results of this work could dictate specific requirements for retrieval machinery.

ACKNOWLEDGMENTS

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